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A METHOD OF CALCULATING THE BIOLOGICAL SHIELD OF LINEAR PROTON ACCELERATORS WITH STRONG FOCUSING

by

V. N. Lebedev, V. V. Mal'kov, B. S. Sychev

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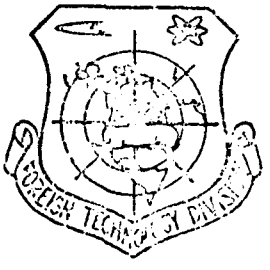

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А а	*А а*	A, a	Р р	*Р р*	R, r
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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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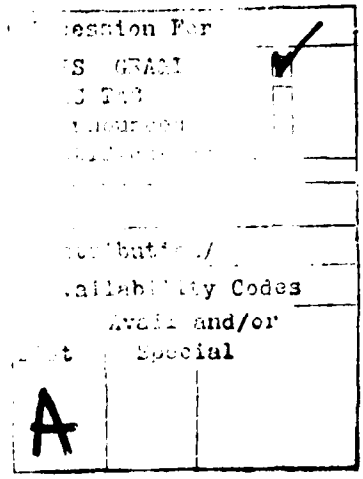
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh^{-1}
cos	cos	ch	cosh	arc ch	cosh^{-1}
tg	tan	th	tanh	arc th	tanh^{-1}
ctg	cot	cth	coth	arc cth	coth^{-1}
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log



A METHOD OF CALCULATING THE BIOLOGICAL SHIELD OF LINEAR PROTON ACCELERATORS WITH STRONG FOCUSING

V. N. Lebedev, V. V. Mal'kov, B. S. Sychev

Formulas for calculating the biological shield of linear proton accelerators with an energy of up to 1 heV [sic] are presented in this work. A plan for calculating a shield is developed. A graphical explanation which significantly simplifies the estimate calculations of the shield is given for the basic mathematical formulas. An example of calculating the shield of a high-current linear proton accelerator with an energy of 800 meV [sic] is shown. The presented method allows estimate calculations of a shield to be conducted effectively with alternative designing of the accelerator's structure.

The formalism of calculating a shield differentiates the uniformly distributed losses of a beam and the localized impact points. The actual compound distribution of the protons which, for one reason or another, emerged from acceleration along the length of the accelerator may be presented in the form of a specific combination of evenly distributed and local losses.

Calculating a shield in the case of evenly distributed losses of a beam.

Taking only the uniform losses of a beam of accelerated particles into consideration, the linear accelerator with strong focusing may be represented by an infinite anistropic line source. The line

density of secondary penetrating radiation-neutrons-of that source is determined by the expression:

$$F(E) = \frac{I_p}{L} \eta_1 B(E_p). \qquad (1)$$

Here I_p is the proton flux, proton/s; L is the acceclerator's length; η_1 is the coefficient which characterizes the value of uniformly distributed losses; $B(E_p)$ is the output of neutrons per proton which emerged from the acceleration as a function of the protons' energy.

The output of neutrons $B(E_p)$ is the sum of evaporative $B_И(E)$ and cascading $B_К(E)$ neutrons per proton. The functions $B_И(E)$ and $B_К(E)$ (Fig. 1) are plotted on the basis of [1-3].

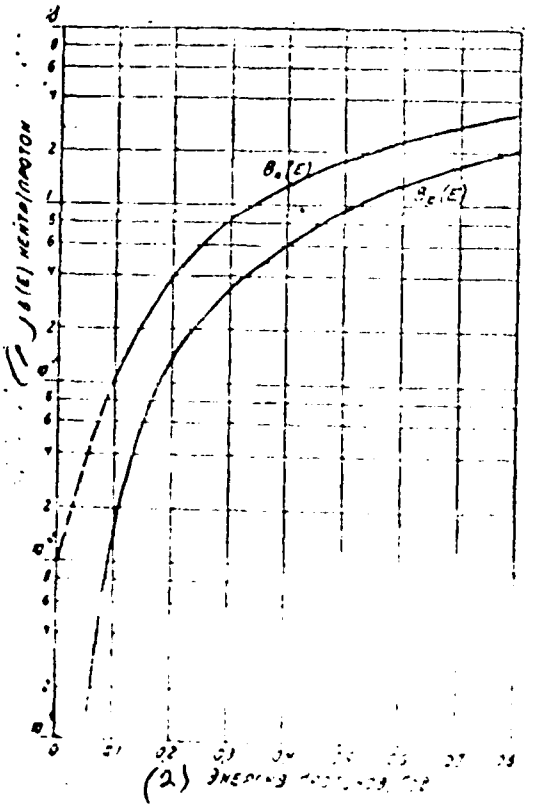


Fig. 1. The dependence of the evaporation and cascading neutrons' output on the protons' energy.

KEY: (1) B(E) neutron/proton; (2) Proton energy, in GeV.

The angular distribution of evaporative neutrons (0.025 eV < E < <20 meV) is customarily considered isotropic. In accordance with this, we write the evaporative neutrons' flux depression in the form [4]

$$\Phi_n(r, E, d) = \frac{F_n(E)}{2\pi r} \left[\operatorname{seci}\left(\frac{d}{\lambda}\right) \right] \qquad (2)$$

A function of the integral secant of seci (d/λ) is tabulated in [4-5] and presented in Fig. 2.

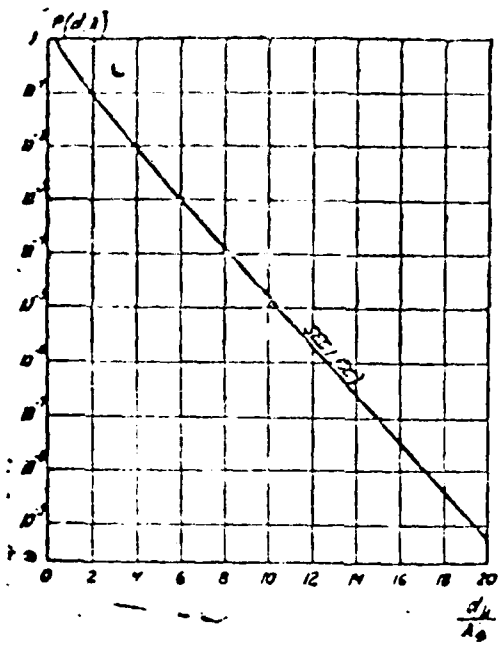


Fig. 2. A function of the integral secant of P (d, λ).

In the formula (2) r is the distance from the axis of a proton beam to a point under consideration beyond the shield; d is the shield's thickness; λ is the evaporative neutrons' relaxation length.

The evaporative neutrons' relaxation lengths are not determined experimentally. Based on the fact that the evaporative neutrons' spectrum is close to the fission spectrum, we used the relaxation length for neutrons of the fission spectrum λ_{II} which is known for many materials [6, 7] as λ . The fission spectrum's λ_{II} values are presented in Table 1 for materials which found application in the shield of proton accelerators.

We write the law of flux density depression of cascading neutrons which are generated by an anisotropic liner source in the following manner

$$\Phi_k = \frac{F_k(E)}{r} \int_0^{\pi} f(\theta) e^{-\frac{r}{\lambda_k} \sec\theta} d\theta. \qquad (3)$$

Table 1. Relaxation lengths for neutrons of a fission spectrum $\lambda_д$ and the build-up factors of $B_{пр}$ and $B_з$.

Материал в защите (1)	Объемный вес, кг/м³ (2)	Содержание водорода, кг/м³ (3)	$\lambda_д$, см (4)	Факторы накопления (5) $B_{пр}$	$B_з$
Земля (6)	1720	20	18	1,2	3,9
Бетон (7)					
обычный (8)	2380	15	12	2,9	5,5
гематитовый (9)	3600	20	9	8,0	10,3
на стальном скрапе (10)	5350	30	7	8,0	10,0

KEY: (1) Material in the shield; (2) Weight by volume, kg/m^3; (3) Hydrogen content, kg/m^3; (4) cm; (5) Build-up factors; (6) Earth; (7) Concrete; (8) Common; (9) Hematite; (10) In steel scrap.

Table 2. The relaxation lengths of cascading neutrons $\lambda_к$, in cm.

Материал в защите (1)	Объемный вес, кг/м³ (2)	Содержание водорода кг/м³ (3)	(4) Энергии протонов, Мэв 20	40	60	100	200	300	400	500	600	700	800
Земля (5)	1720	20	15,7	27,8	39,7	59,1	62	66,6	70,6	73,5	72,2	69,5	67,4
Бетон (6)													
обычный (7)	2380	15	12,3	21,3	30,2	44,0	47	53	58,5	61	60	57,8	56
гематитовый (8)	3600	20	10,2	17,1	23,7	32,7	35,5	39,7	41,0	45,8	45	43,3	42
на стальном скрапе (9)	5350	30	9,7	13,8	18,9	21,5	27,8	30,0	33,2	34,6	34	32,7	31,7

KEY: (1) Material in the shield; (2) Weight by volume, kg/m^3; (3) Hydrogen content, kg/m^3; (4) Energy of the protons, in meV; (5) Earth; (6) Concrete; (7) Common; (8) Hematite; (9) In steel scrap.

Formula (3) considers the angular distribution of cascading neutrons $f(\theta)$ [8], the analytical expression of which is presented in the form [11].

$$\left.\begin{aligned} 2\pi f(\theta) &= 0{,}2 + 0{,}93\cos\theta + 1{,}81\cos^2\theta; \quad 0 < \theta < \frac{\pi}{2}; \\ 2\pi f(\theta) &= 0{,}2 + 0{,}15\cos\theta; \quad \frac{\pi}{2} < \theta < \pi. \end{aligned}\right\} \qquad (4)$$

The expression which stands below the integral sign in formula (3), is integrated numerically. The results of the computations are presented in Fig. 3. We used the cascading neutrons' relaxation lengths (Table 2) from [1] for the calculations.

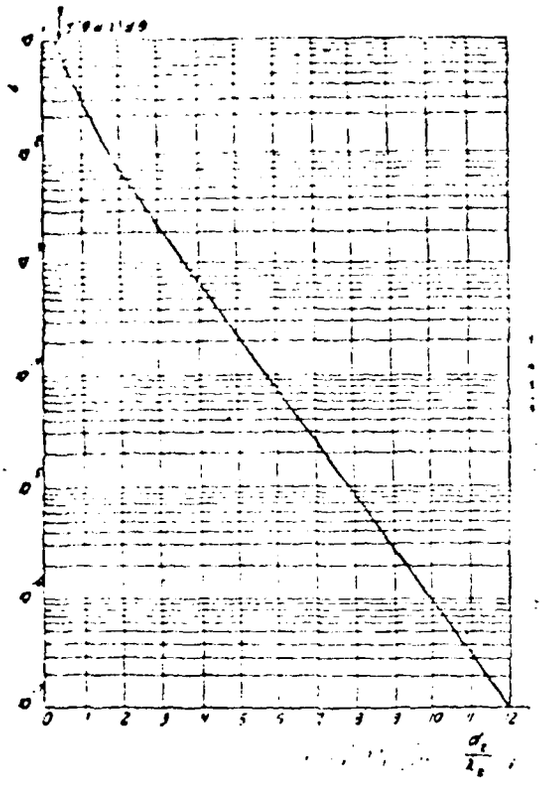


Fig. 3. Integral function of $f(\vartheta)\, e^{-d_K \lambda_K \sec\vartheta} \left(\int_0^{\pi} \varphi(\vartheta, d, \lambda)\, d\vartheta \right)$

Calculating a shield at localized impact points of a beam

The localized impact points of a beam are formed in areas of the placement of beam gates, Faraday cylinders, and other devices which completely or partially absorb beams. These devices, by virtue of the small dimensions in comparison with the distance to the point under consideration beyond the shield, may be considered point sources of neutrons which are anistropic for cascading and isotropic for evaporative neutrons.

The flux depression of evaporative neutrons from the source is described by the expression:

$$\Phi_н(E_p, r) = \frac{I_p B_н(E) \eta_2}{4\pi r^2} e^{-d/\lambda_н}. \qquad (5)$$

The flux depression of high-energy neutrons ($E \geq 20$ meV) for these same conditions may be presented in the form

$$\Phi_к(E_p, \vartheta, r) = \frac{I_p \cdot B_к(E) \eta_2}{r^2} f(\vartheta) e^{-d/\lambda_к}. \qquad (6)$$

In formulas (5) and (6) r is the distance from the source to the point under consideration beyond the shield; d is the shield's thickness; $f(\theta)$ is the angular distribution function of cascading neutrons determined by formula (4); η_2 is the coefficient which characterizes the value of a beam's localized impact points. The remaining designations are the same.

A scheme for calculating a shield

1. Values of evenly distributed and localized losses of an accelerator's beam as well as the arrangement of localized losses along the accelerator's length are determined.

2. The entire length of the linear accelerator is divided into sections. The larger these sections, the more exact the calculation of a shield. It is quite sufficient to select 5-6 sections for estimated calculations.

3. The densities of the line sources $F_н$ (1) and $F_К$ (1) are calculated for each section according to formula (1) and with the help of the graphs (see Fig. 1). It is assumed that the density of the source is constant along each section's length.

4. For each value of the line density F_1 (1), the thickness of the shield is calculated according to formulas (2) and (3) based on the ration:

$$\Phi_{\text{к}}(r, E, d)\cdot(1 + B_{\text{пр}}) = \Phi_{\text{п.д.у}}; \quad (7)$$

$$\Phi_{\text{к}}(r, E, d)\cdot(1 + B_{\text{з}}) = \Phi_{\text{п.д.у}}. \quad (8)$$

Here $B_{пр}$ is the build-up factor of intermediate neutrons; $B_з$ is the build-up factor of decelerated groups of radiations ($E < 20$ meV); $\Phi_{\text{п.д.у}}$ is the maximum permissible flux densities of neutrons beyond the shield.

The values of $B_{пр}$ and $B_з$ obtained on the basis of [1, 9, and 10] are presented in Table 1 and the recommended values of $\Phi_{\text{п.д.у}}$ - in Table 3.

Table 3. The recommended values of the maximum-permissible neutron fluxes.

(1) Группа нейтронов	(5) Энергия излучения, *мэв*	Проектная плотность потока, *нейтр/см²* для помещений (6)			
		основных для постоянной работы с источником излучений (кат. А–1) (6a)	полуобслуживаемых (кат. А–2) (6b)	необслуживаемых (кат. А–2Т) (6c)	смежных с постоянным пребыванием персонала (кат. Б) (6d)
Быстрые (2)	10	10	20	100	1
Очень быстрые (3)	200	5	10	50	0,5
(4)	500	3	6	30	0,5
Сверхбыстрые	2000	1,5	3	15	0,15

KEY: (1) Group of neutrons; (2) Fast; (3) Very fast; (4) Superfast; (5) Energy of the radiation; (6) The rated flux density, neutrons/cm², for places ...; (6a) which are basic for constant operation with the source of radiation (catalyst A-1); (6b) which are semi-serviceable (catalyst A-2); (6c) which are unserviceable (catalyst A-2); (6d) which are adjacent with a constant stay of personnel (catalyst B).

The shield's thickness d is found with the assigned values of r from relationships (2) and (3) and the larger of d_{11} and d_K is taken as the actual value of d in each section.

5. An envelope (curve) which is also an estimated outline of the shield from a beam's evenly distributed losses is plotted according to values of the shield's thickness d calculated for each section of the accelerator.

6. The shield is calculated by formulas (5) and (6) in areas of the beam's localized impact points; a final outline of the shield from the evely distributed and localized sources is plotted.

An example of calculating an 800-meV accelerator's radiation shield

Initial data. Intensity $I_p = 10^{14}$ proton/s; energy of injection $E_1 = 0.7$ meV; maximum energy of the protons $E_2 = 800$ meV.

The acceleration system has two accelerating structures. The first accelerates the protons from an energy of 0.7 meV to 200 meV, the second from 200 meV to 800 meV. The lengths of the accelerating structures are 120 and 180 m respectively (see Fig. 4).

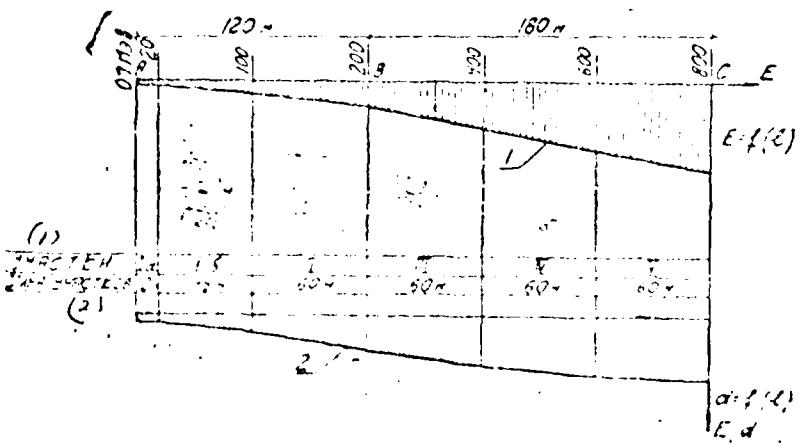


Fig. 4. To calculate a shield with evenly distributed losses: 1 - The dependence of the protons' energy on the length of the accelerator; 2 - Calculated outline of the shield.
KEY: (1) Sections; (2) Length of the sections.

Calculation. 1. We take the value of the evely distributed losses η_1 = 1%.

2. We divide the entire length of the accelerator into 5 sections. The length of each section is 60 m. The boundary energy values equal 0.7, 100, 200, 400, 600, 800 meV (see Fig. 4).

3. We determine the output of evaporative and cascading neutrons for each of the accelerator's section by the graphs (see Fig. 1):

$E = 20$ мэв $\quad B_н = 10^{-3}, \quad B_к = < 10^{-4};$

$E = 100$ мэв $\quad B_н = 1{,}4 \cdot 10^{-1}, \quad B_к = 2{,}5 \cdot 10^{-2};$

$E = 200$ мэв $\quad B_н = 6{,}5 \cdot 10^{-1}, \quad B_к = 2 \cdot 10^{-1};$

$E = 400$ мэв $\quad B_н = 1{,}7, \quad B_к = 8{,}5 \cdot 10^{-1};$

$E = 600$ мэв $\quad B_н = 3{,}2, \quad B_к = 1{,}6;$

$E = 800$ мэв $\quad B_н = 5, \quad B_к = 2{,}5.$

Рис 5

4. We calculate the linar source densities for each section from the formula (1):

E = 20 meV

$$F_н = \frac{10^{14} \cdot 0{,}01 \cdot 10^{-3}}{300} = 3{,}3 \cdot 10^{7} \text{ proton/m} \cdot \text{s}.$$

$$F_к \approx 0;$$

E = 100 мэв

$$F_н = \frac{10^{14} \cdot 0{,}01 \cdot 1{,}4 \cdot 10^{-1}}{300} = 4{,}7 \cdot 10^{8} \text{ proton/m} \cdot \text{s}$$

$$F_к = \frac{10^{14} \cdot 0{,}01 \cdot 2{,}5 \cdot 10^{-2}}{300} = 8{,}4 \cdot 10^{6} \text{ proton/m} \cdot \text{s}$$

$E = 200$ мэв $\quad F_н = 3{,}2 \cdot 10^{9}, \quad F_к = 6{,}7 \cdot 10^{8};$

$E = 400$ мэв $\quad F_н = 5{,}7 \cdot 10^{9}, \quad F_к = 2{,}9 \cdot 10^{9};$

$E = 600$ мэв $\quad F_н = 1{,}1 \cdot 10^{10}, \quad F_к = 5{,}4 \cdot 10^{9};$

$E = 800$ мэв $\quad F_н = 1{,}7 \cdot 10^{10}, \quad F_к = 8{,}4 \cdot 10^{9}.$

5. We select the $\Phi_{доз}$ value on the surface of Earth which equals 20 neutrons/cm^2·s. We find the build-up factors' value for Earth from Table 1: $B_{пр}$ = 1.2; $B_з$ = 3.9. We determine the permissible fluxes for evaporative and cascading neutrons on the surface of Earth by formulas (7) and (8):

$$\Phi_{\text{п}} = \frac{20}{1,2} = 17; \quad \Phi_{\text{к}} = \frac{20}{3,9} = 5.$$

6. We calculate the shield's thickness $d_{\text{п}}$ and $d_{\text{к}}$ for each section of the accelerator by formulas (2) and (3) with the help of Figs. 2 and 3. Upon calculating, we assign a value for r, then we conduct repetitive calculations for the purpose of obtaining the results r = a + d, where a is the distance from the source to the shield.

E = 20 meV

We assign the value r = 2.5 + 2 = 4.5 m. We determine $d_{\text{п}}$.

From formula (2) we obtain the relationship:

$$\text{sec}\,i\left(\frac{d_{\text{п}}}{\lambda_{\text{д}}}\right) = \frac{\Phi_{\text{п}} \cdot 4\pi r}{F_{\text{п}}(E)} = 3 \cdot 10^{-1}.$$

From the graph (see Fig. 2) we determine $d_{\text{п}}/\lambda_{\text{д}} = 1.2$. From Table 1 $\lambda_{\text{д}} = 18$ cm; consequently, $d_{\text{п}} = 18 \cdot 1.2 = 22$ cm.

We correct the value of r:

$$r = 2,5 + 0,5 = 3,0 \text{ м};$$

$$\text{sec}\,i\left(\frac{d_{\text{п}}}{\lambda_{\text{д}}}\right) = \frac{17 \cdot 4\pi \cdot 300}{3,3 \cdot 10^{3}} = 2 \cdot 10^{-1}.$$

From Fig. 2 $d_{\text{п}}/\lambda_{\text{д}} = 1.4$; $d_{\text{п}} = 18 \cdot 1.4 = 25$ cm. The value $d_{\text{к}} = 0$, because $F_K = 0$ when the proton energy is E = 20 meV.

E = 100 meV

We take r = 2.5 + 1.0 = 3.5 m. We determine $d_{\text{п}}$.

$$\text{sec}\,i\left(\frac{d_{\text{п}}}{\lambda_{\text{д}}}\right) = \frac{17 \cdot 4\pi \cdot 350}{4,7 \cdot 10^{3} \cdot 10^{3}} = 1,6 \cdot 10^{-2}.$$

From Fig. 2 $d_{\text{п}}/\lambda_{\text{Л}} = 3.5$; $d_{\text{и}} = 18 \cdot 3.5 = 56$ cm.

We take $d_{\text{и}} = 60$ cm. We determine $d_{\text{к}}$.

From formula (3) we obtain the relationship:

$$\int_0^{\pi} f(\theta) e^{-d_{\text{к}}/\lambda_{\text{к}} \cos\theta} d\theta = \int_0^{\bar{\theta}} \varphi(d, \lambda, \eta) d\eta$$

$$= \frac{\Phi_{\text{к}} r}{F_{\text{к}}(E)} = \frac{5 \cdot 450}{8{,}4 \cdot 10^{6} \cdot 10^{-2}} = 2{,}1 \cdot 10^{-3}.$$

We find $d_{\text{к}}/\lambda_{\text{к}} = 1.2$ from the graph (Fig. 3). When the energy is E = 100 meV for soil $\lambda_{\text{к}} = 59.1$ cm. Then $d_{\text{к}} = 59.1 \cdot 1.2 = 70$ cm.

In a similar manner, we determine the shield's thicknesses $d_{\text{и}}$ and $d_{\text{к}}$ for proton energy of 200, 400, 600, and 800 meV. The values of these thicknesses are the following:

E = 200 *мэв*	$d_{\text{и}} = 95$ *см*,	$d_{\text{к}} = 290$ *см*;
E = 400 *мэв*	$d_{\text{и}} = 105$ *см*,	$d_{\text{к}} = 400$ *см*;
E = 600 *мэв*	$d_{\text{и}} = 115$ *см*,	$d_{\text{к}} = 450$ *см*;
E = 800 *мэв*	$d_{\text{и}} = 120$ *см*,	$d_{\text{к}} = 460$ *см*.

We take the larger values of $d_{\text{и}}$ and $d_{\text{к}}$ as the actual value of the shield's thickness. Those are:

E = 20 *мэв*	d = 25 *см*;	E = 400 *мэв*	d = 400 *см*;
E = 100 *мэв*	d = 70 *см*;	E = 600 *мэв*	d = 450 *см*;
E = 200 *мэв*	d = 290 *см*;	E = 800 *мэв*	d = 460 *см*.

We plot these values of d on Fig. 4 and construct the estimated dependence (2) of the shield's thickness on the length of the accelerator with evenly distributed losses, $\eta_1 = 1\%$ of the full intensity of $I_p = 10^{14}$ protons/s.

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